Nocibur: High Efficiency Lasing with a Strongly Tapered Helical Undulator

Nicholas Sudar, P. Musumeci, J. Duris

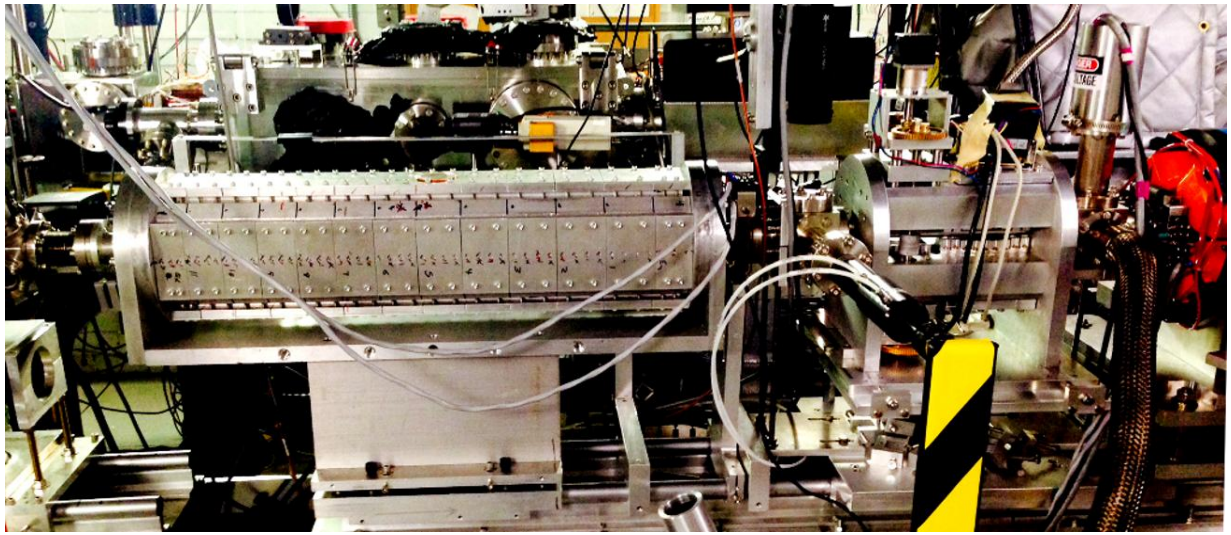
University of California, Los Angeles
department of Physics and Astronomy

Outline of Talk

- Introduction to the Nocibur concept: the physics and the uses/justification
- Preparation for the first experimental run
- Procedure: the first experimental run
- Results: the first experimental run
- Future plans

Introduction
Nocibur: Rubicon Backwards

- Highly efficient optical to electric energy conversion in Rubicon IFEL acceleration (increased e-beam peak power by ~150%)
- The reverse process: electrical to optical energy conversion could result in a highly efficient laser amplifier: (FEL ρ~1e-4, Nocibur~0.35)
  Inverse Inverse Free Electron Laser

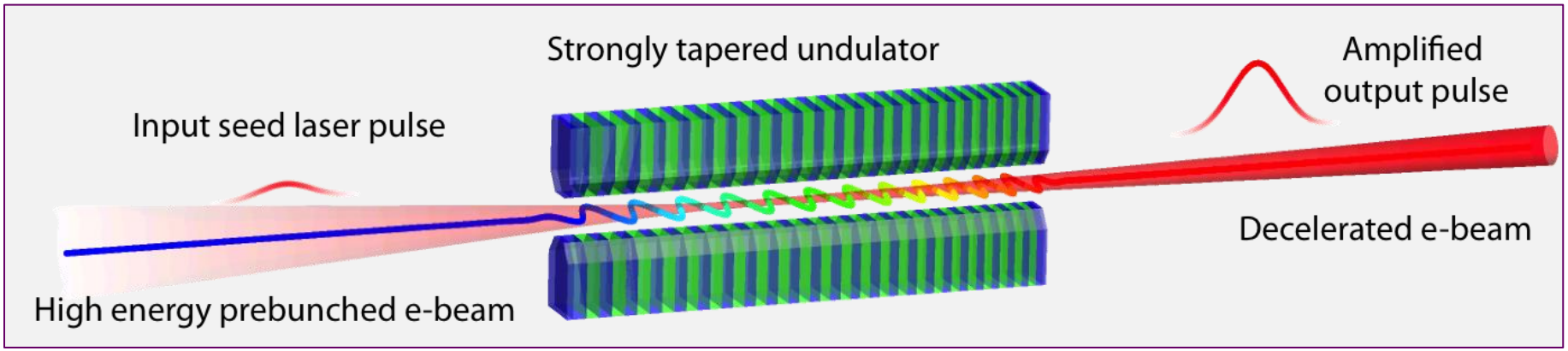


- Where does the energy go? (stimulated emission & FEL resonance condition)
- Nocibur – Low gain – field growth small compared to seed
- Acknowledgements

Collaborators: A. Murokh, A. Gover, J. B. Rosenzweig, I. Gadjev, Y. Sakai, all ATF staff
Funding agencies: DOE

Nocibur →TESSA

- Inverse IFEL = ~~FEL~~ TESSA (**T**apering **E**nhanced **S**timulated **S**uperradiant **A**mplification)
- E-beam rapid deceleration → laser amplification
- Requires seed pulse of high intensity (larger than FEL P_{SAT})
- E-beam can be prebunched, or it can be bunched in the first few undulator periods



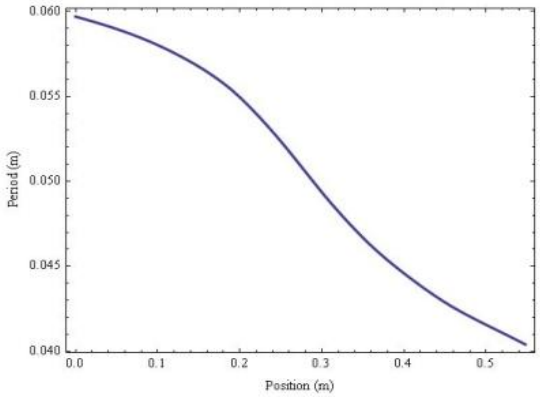
- High efficiency conversion of electron beam energy to coherent radiation opens door to very high average power light sources.
- Wavelength set by e-beam energy and resonant condition -> wide tunability
  - High average power IR and visible lasers.
  - X-rays.
  - EUV-L applications.

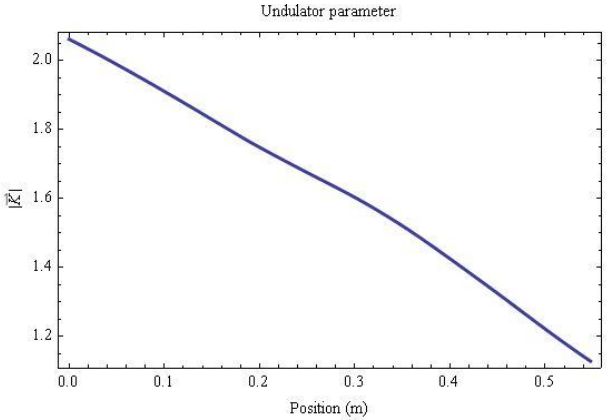
The IFEL tapering equations: deceleration

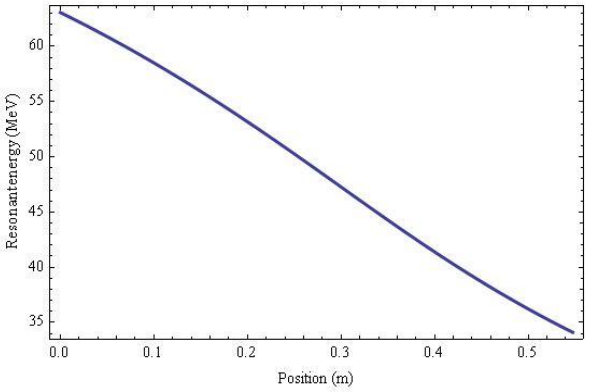
- $$\frac{\partial \gamma_r^2}{\partial z} = -2kK_l K \sin(|\psi_r|)$$
- Choose resonant phase: -Pi/4 (trade off between gradient and size of pondermotive bucket/trapping)
- Choose constant resonant phase tapering
- $$\frac{\partial \psi}{\partial z} = k_w - k(1+K^2)/2\gamma_r^2 \rightarrow 0$$
- Period tapering set by Rubicon so optimization only done for gap tapering
- $$\frac{\partial K}{\partial z} = -2\pi K_l \sin(|\psi_r|)/\lambda_w - \frac{(1+K^2)}{2K\lambda_w}\frac{\partial \lambda_w}{\partial z}$$

Parameter	Value
E-beam energy	65 to 35 MeV
E-beam current	100 A (400 A compressed)
Laser Focal intensity	4 TW/cm²
Laser wavelength	10.3 µm
Rayleigh range	30 cm
Laser waist	1.0 mm
Input peak power	100 GW
Output peak power	102GW (108 GW compressed)

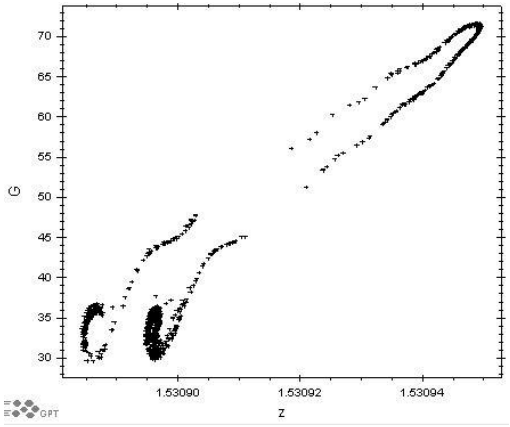
- 1D Model



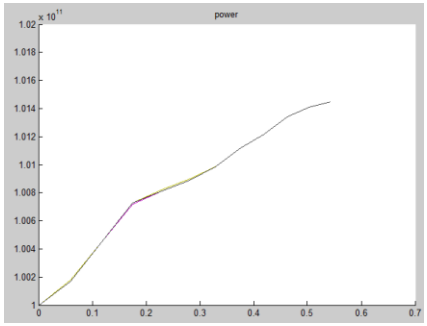


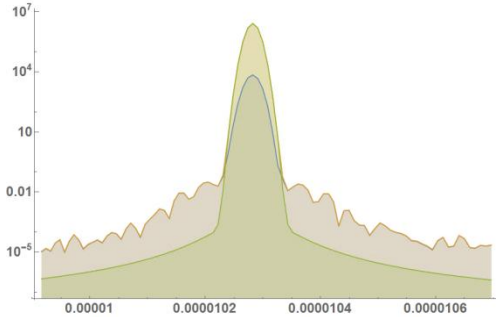


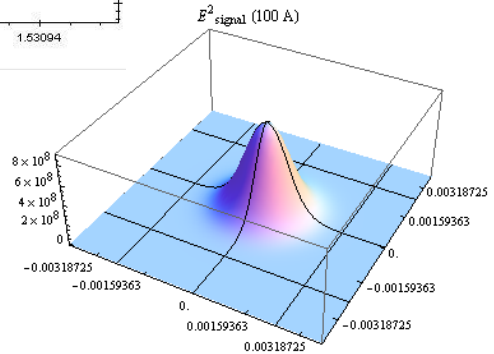
- GPT Simulation

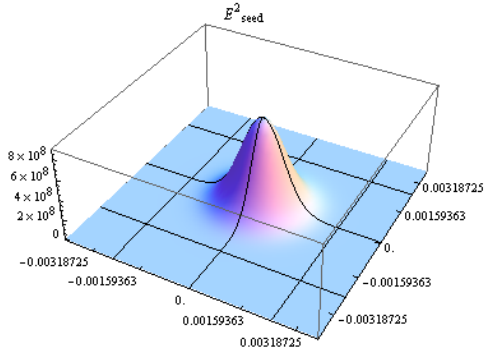


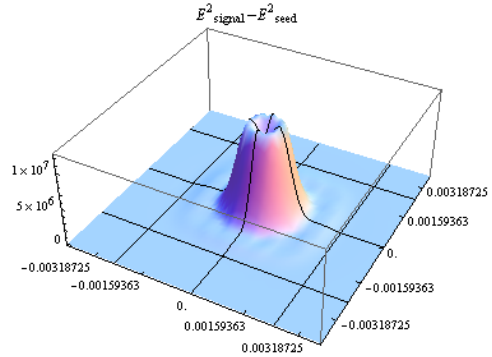
Genesis Simulations (100A)



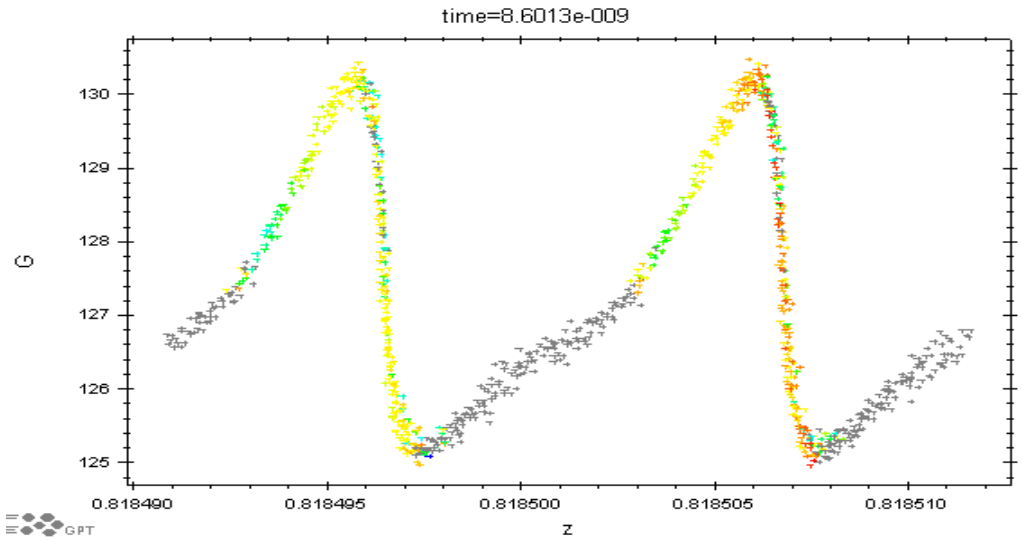


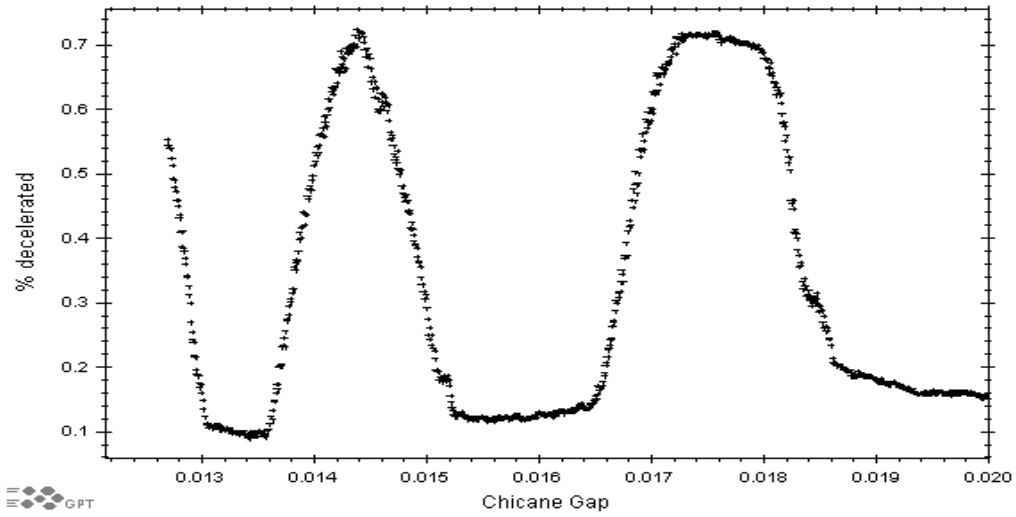




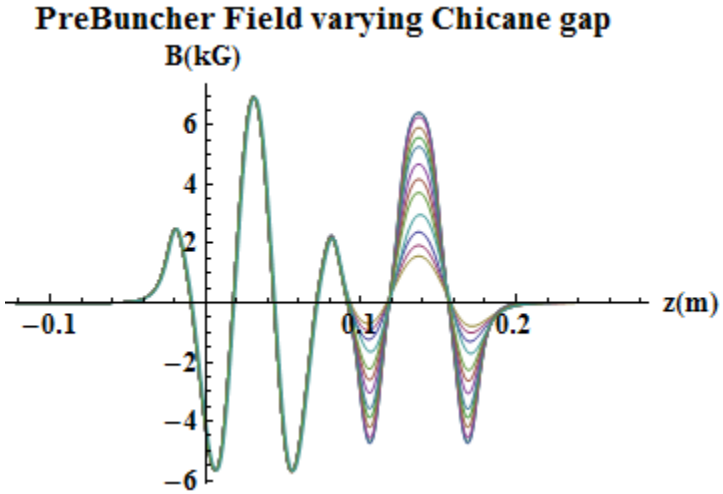


Pre-bunching – Laser Focusing maximizing the interaction





~30 cm



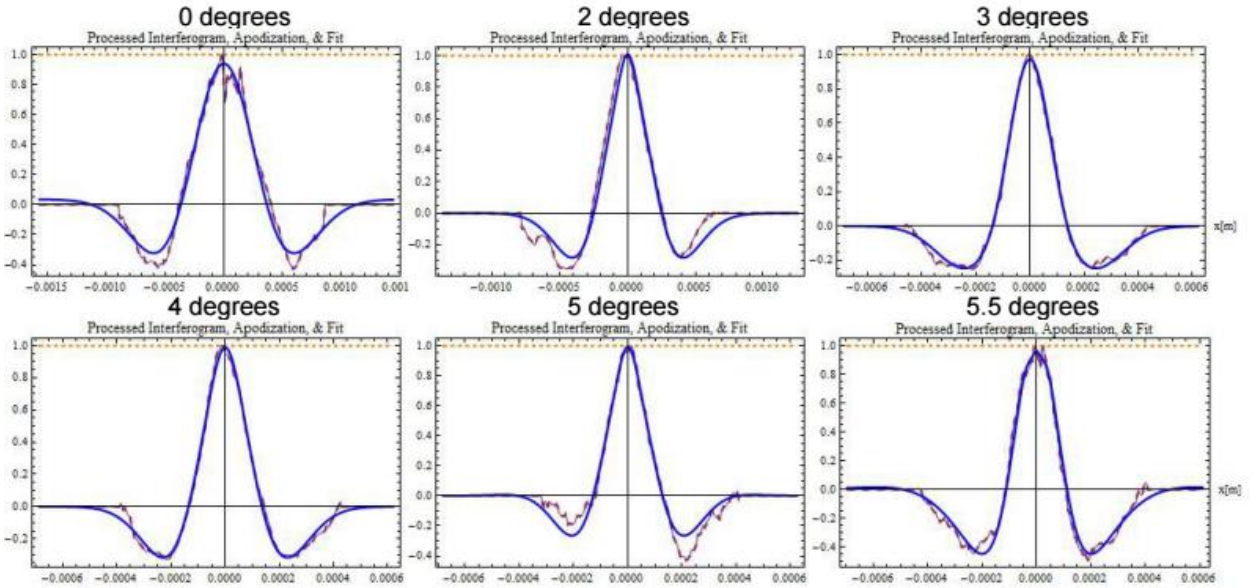
BLIS measurements-Maximizing Current

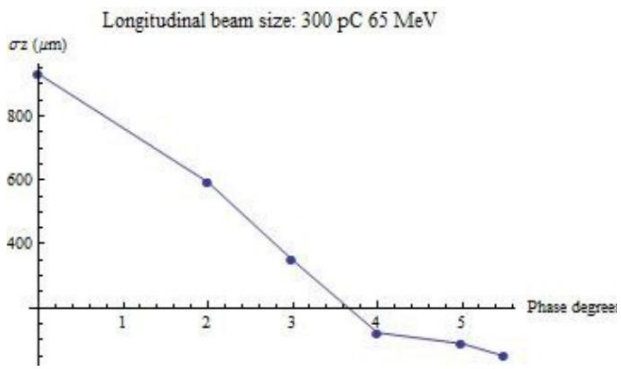
- Auto-correlation measurements taken near undulator entrance, CTR radiation measured by bolometer

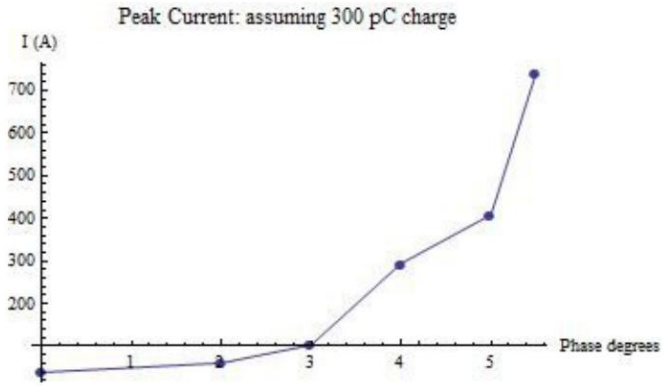
- Increase chirp, varying linac phase from minimum energy spread (phase=0 degrees)

- 3 Gaussian fit to get approximation of bunch length

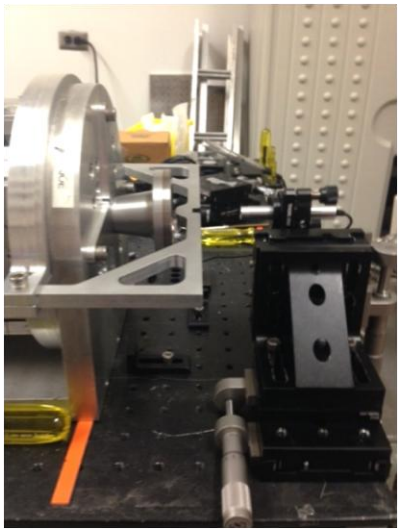
- Didn't look for emittance growth, ran with pellicle

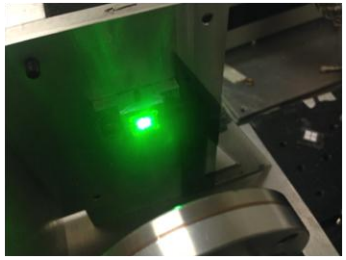


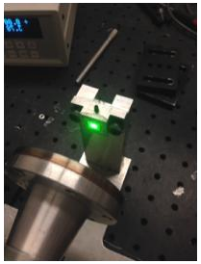


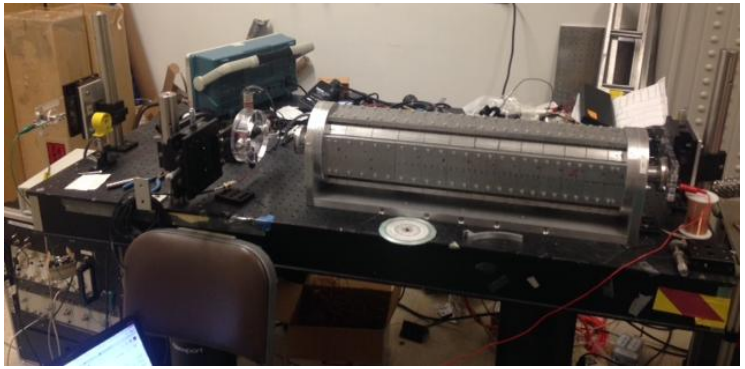


Tuning the undulator

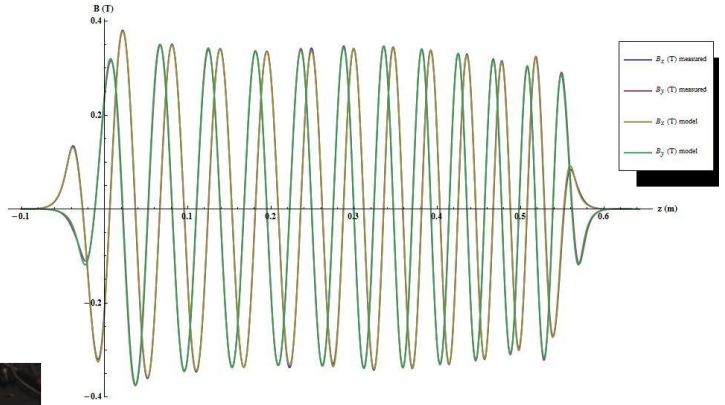


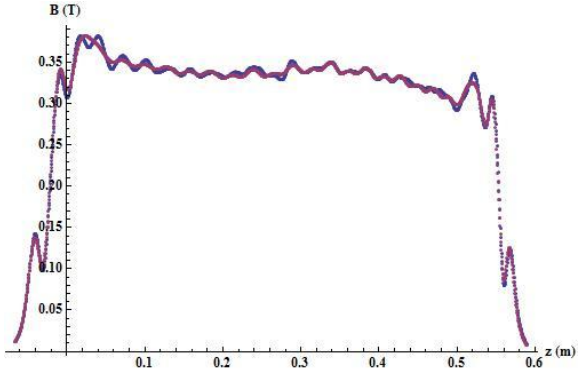




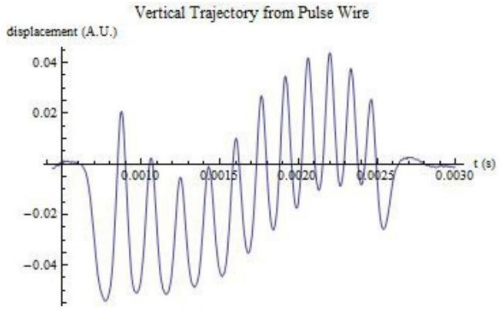


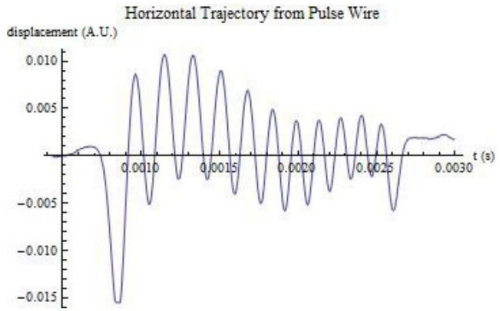
- Comparison between radia model and hall probe scans of undulator





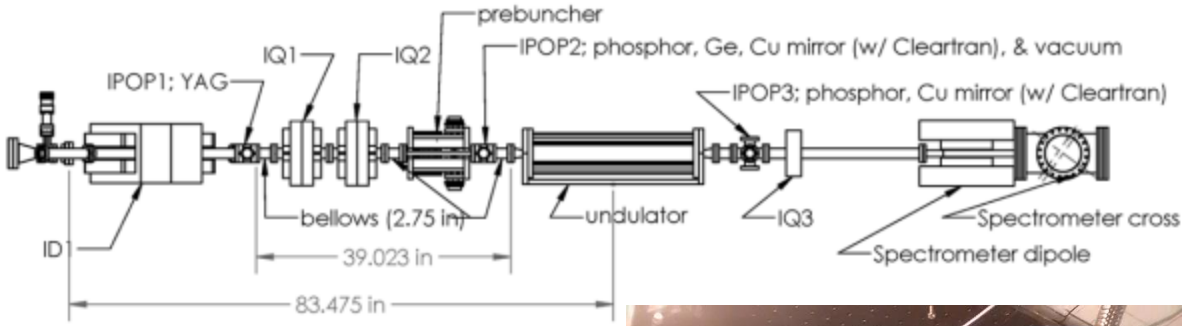
- Pulse wire 2nd Integral – tuning entrance and exit magnets to minimize offset and angle



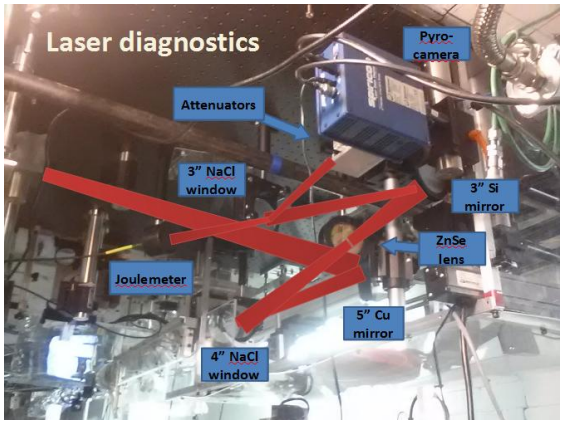


Experimental Run: alignment, installation, timing

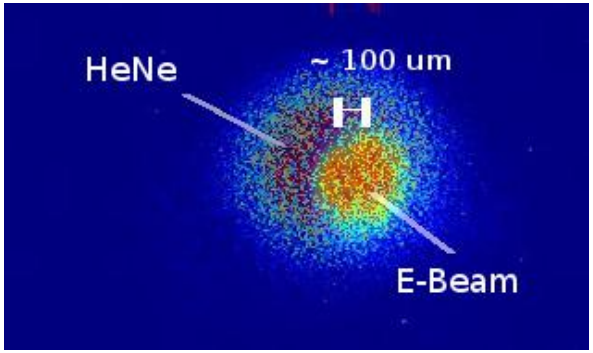
- Undulator and Pre Buncher are aligned with irises mounted to undulator body to match geometric center to beamline HeNe

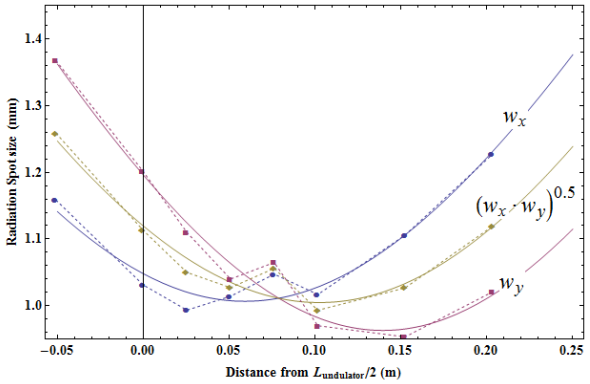


- Tapering optimized for laser waist at center of undulator
- Moving NaCl lens upstream we can move waist position
- Imaging CO2 regen, moving pyro camera on rail we can characterize the laser
- Fits: $|zWaistx - zWaisty| = 0.08$ m
  $wx = 1.007$ mm $wy = 0.963$ mm
  $M^2 = 1.5$ $zr = 0.3$ m

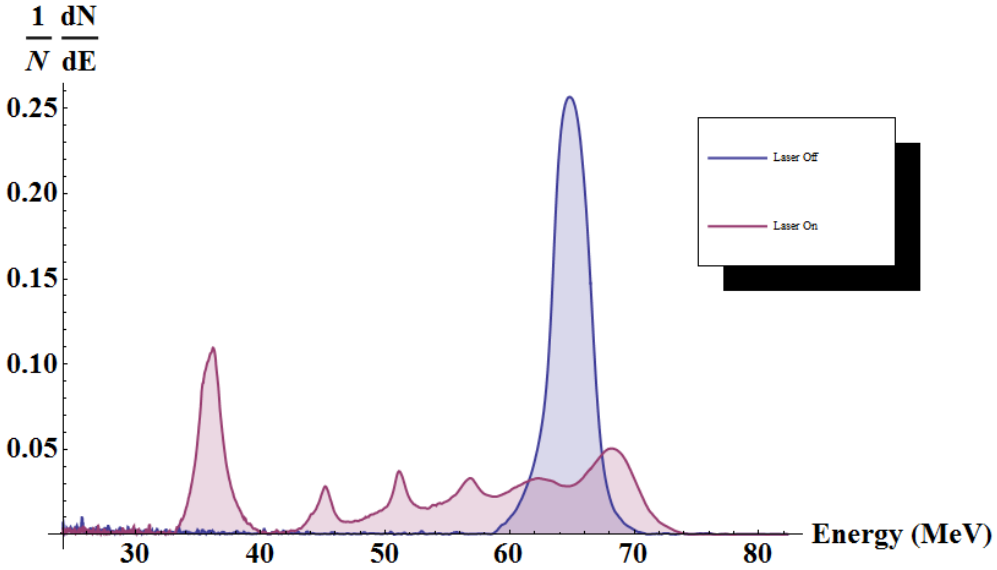


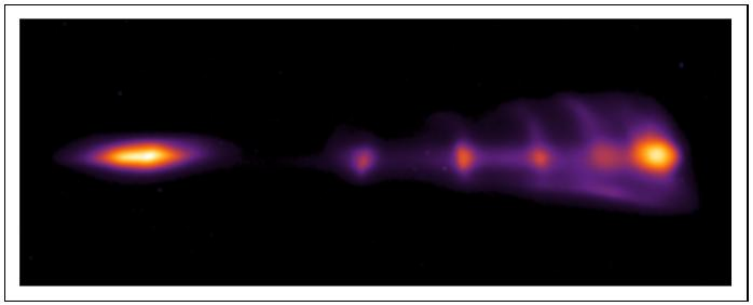
- Rough timing between laser and e-beam: Germanium switch inserted up stream of pre buncher
- Fine timing: vary delay stage in laser room to maximize deceleration interaction





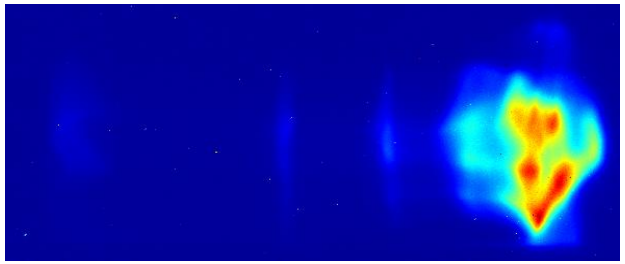
Experimental Run: deceleration results



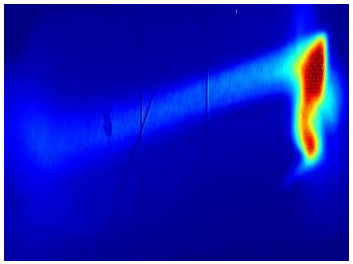


- ~30 % deceleration of 300 pC, 100 A beam from 65 to 35 MeV
- expect this energy extraction to produce ~ 1 GW of 10.3 μm radiation on top of ~ 100 GW → ~3 mJ of energy
- Trapping optimization:
  - Vary PreBuncher gap
    - Potential motor/gear slippage creates kick and mismatch with GPT simulation
  - Vary lens position
    - Possible clipping through PreBuncher pipe
  - Increase current
    - emittance growth

Spectrometer Data - 5 degree chirp



Compression at FPOP3



Experimental Run: measuring the radiation

- Plan: Helical undulator produces circularly polarized radiation
- Seed undulator with linearly polarized pulse, use polarizer to separate produced radiation in plane perpendicular to seed.

<u>Why it didn't work:</u>

- Coherent undulator radiation vs. stimulated emission (µJ vs. mJ)

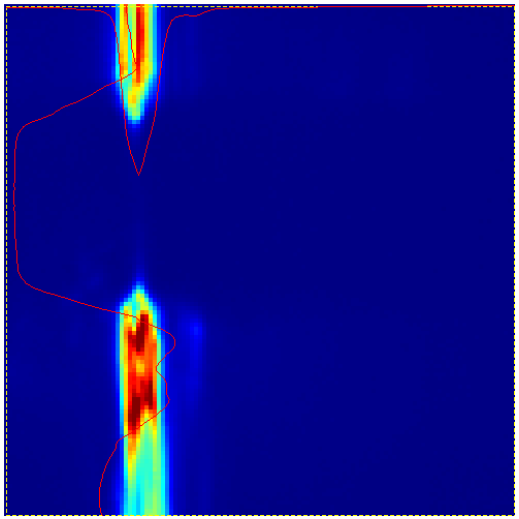
$$E^2 - E_{seed}^2 = (E_{seed} + E_{gain})^2 - E_{seed}^2$$

$$= 2E_{seed}E_{gain} + E_{gain}^2 >> E_{gain}^2$$

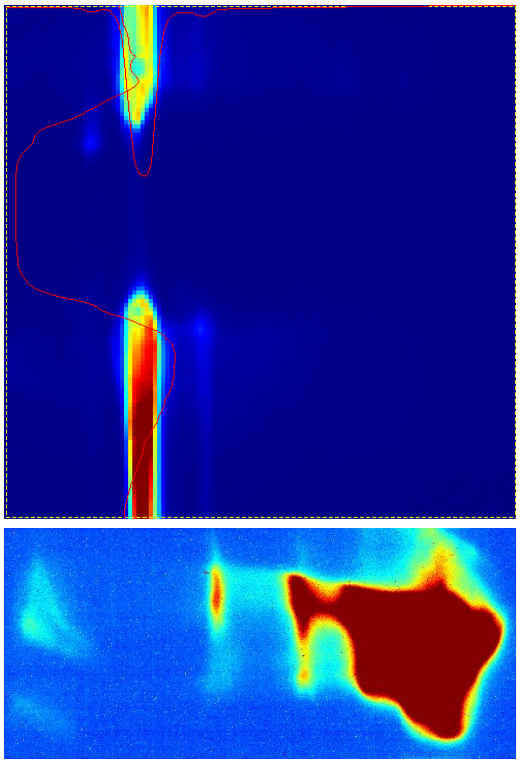
- No correlation between ceiling Joule meter and down stream Joule meter (damage on NaCl window)

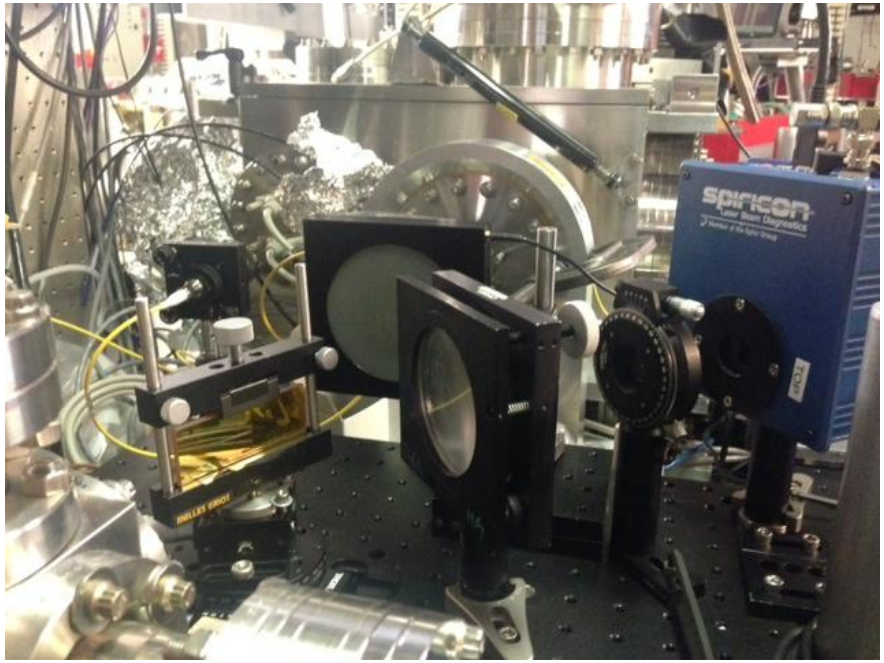
<u>Pyro camera data: Radiation spectrum down stream blocking core of spectrum (no correlation between e-beam on/off)</u>

E-beam Off Laser Energy: 0.782 J



E-beam On Laser Energy: 0.87 J

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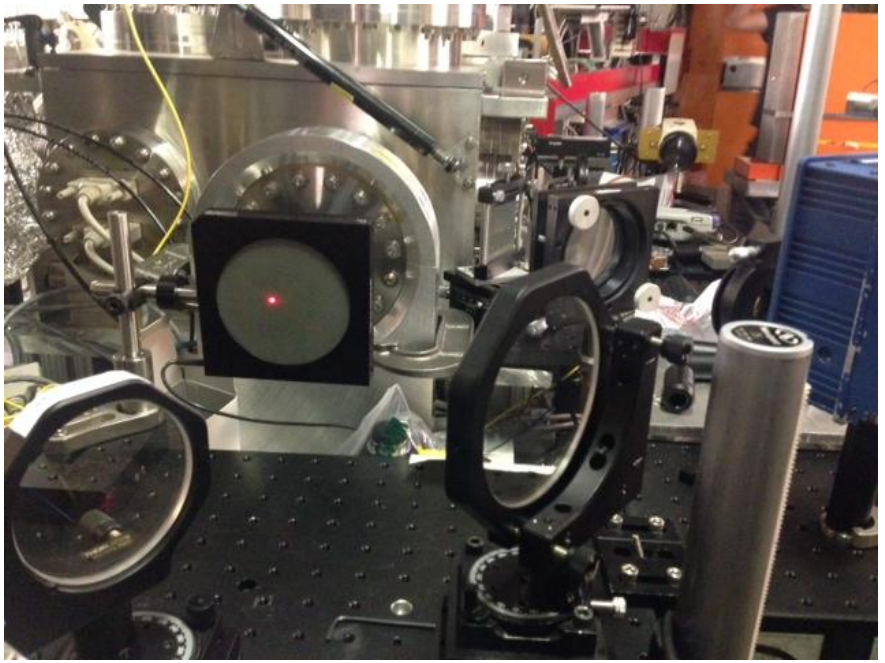
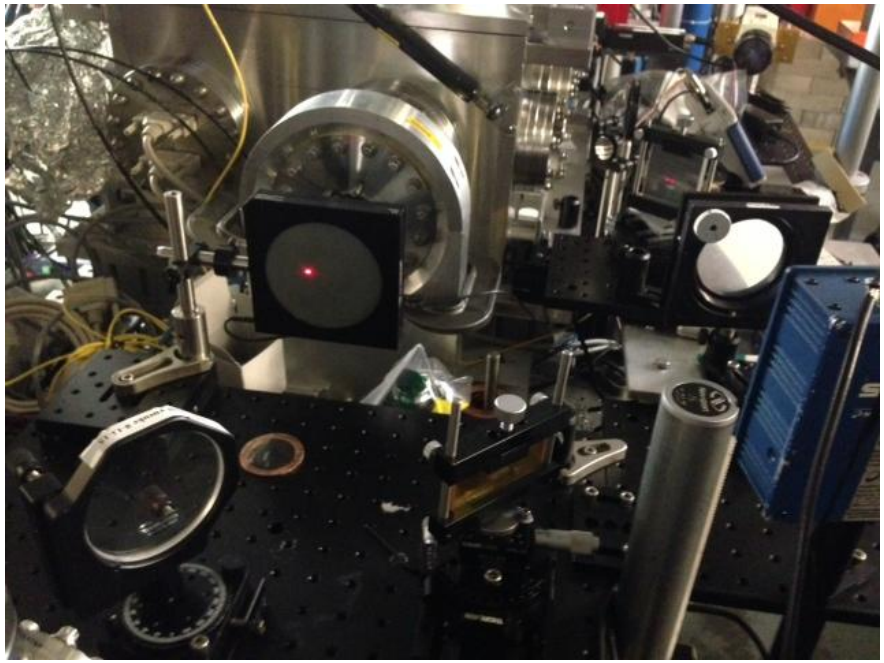
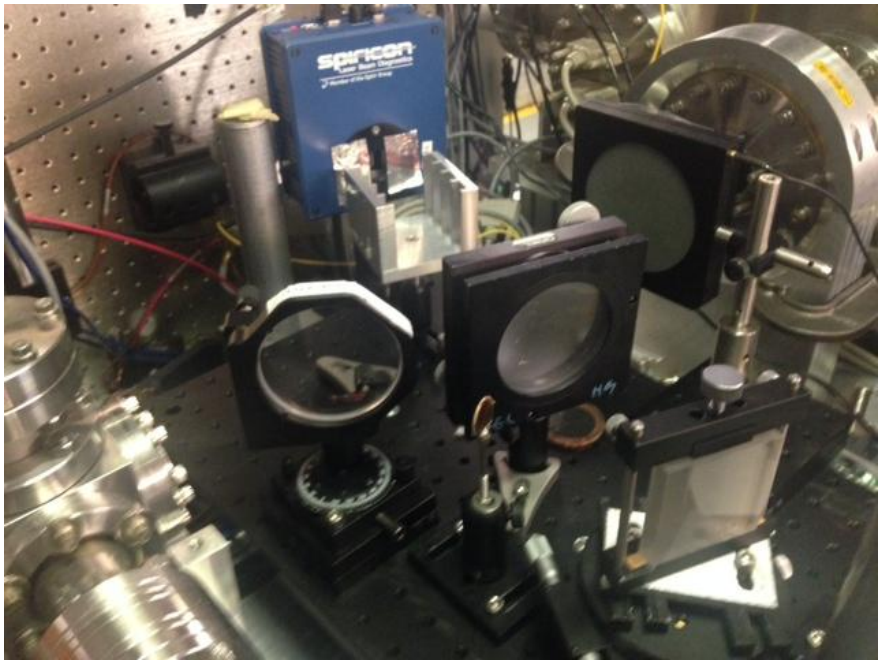
Laser Beam Diagnostics



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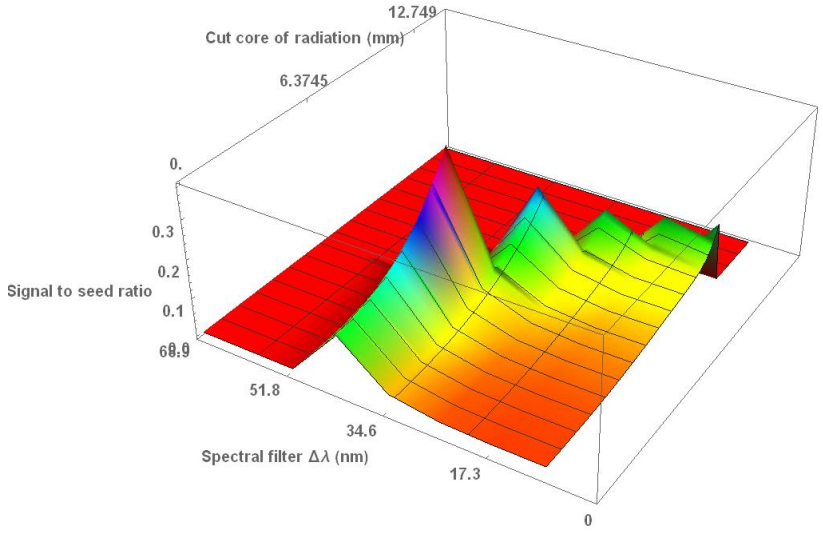
Laser Beam Diagnostics

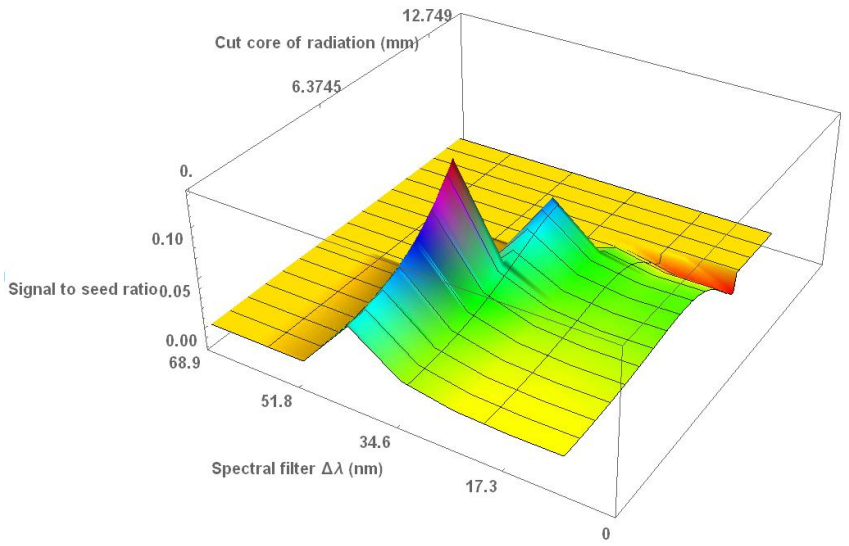
Summary of 1st Run

- Successfully demonstrated 15% electro-optical conversion efficiency. 30% of the beam decelerated from 65 to 35 MeV
- Alignment/Tuning of undulator: Undulator didn't kick!
- Compression: Higher peak current beam suffered from emittance growth
- Linear polarization: Process of Nocibur radiation production is stimulated emission
  - Linear polarization + polarizer measurement scheme was flawed.
  - Measuring produced radiation in this low gain regime is non trivial.

Plans for future run

- Improve capture
  - Fix pre-buncher
  - Better beam tune, elegant optimizations, increase peak current
- Spatial and spectral filtering:
  - Take advantage of diffraction: Core out radiation beam/mirror with hole
  - Take advantage of spectral broadening/side bands





- 1 week installation, 2 week run

Thank you for your attention.
Thank you again to the ATF staff for their work on the first Nocibur run.

Also thank you coffee for helpful contributions